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Automated Measurement System for T1 Characterization

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A computer operated measurement system was developed for the T1 characterization program. Using this automated system, we measured the T1 repeater section crosstalk margin, insertion loss, power sum, line resistance, simplex current, longitudinal currents, crosstalk spectrum, noise voltage distributions, and repeater margin, and made calibration checks. Over 100,000 field measurements have proven this test system to be reliable, versatile, and accurate.

I. INTRODUCTION

As part of the T-Carrier characterization program, T1 repeater section performance measurements were performed in 1977 and 1978. In this paper, we describe the experimental design and equipment implementation for these measurements. Other aspects of this program are described in companion papers.[1] The T1 repeatered line consists of the regenerative sections adjacent to central offices (end sections), and the intermediate sections. Intermediate section measurements performed at manholes are discussed in Section 2 and end-section measurements in the central office are described in Section 3.

The following measurements were performed for each intermediate section:

(*i*) Line resistance and simplex power currents
(*ii*) Longitudinal ac current
(*iii*) Pair insertion loss at various frequencies
(*iv*) Crosstalk coupling losses within the apparatus case slot
(*v*) Crosstalk power sum
(*vi*) Line margin for a test repeater
(*vii*) Bit-rate and half-bit-rate output power of transmitting repeater

(*viii*) Crosstalk spectrum at repeater input
(*ix*) Automatic line buildout current of test repeater
(*x*) Voltage amplitude distribution of crosstalk noise
(*xi*) Service repeater margin and eye opening
(*xii*) Test repeater calibration checks

End sections were characterized by measuring crosstalk power sum, crosstalk margin, and voltage amplitude distribution of crosstalk using separate test equipment designed for single-ended measurements in the central office.

II. INTERMEDIATE SECTION MEASUREMENTS

Analysis of plant records indicates extensive use of 900- and 1100-pair pulp cables for T1 in metropolitan areas.[2] For one-cable operation, previous engineering rules for these cables allowed 200 and 250 T1 systems, respectively. With these large T1 cross sections, an automated measuring system was deemed essential for fast and reliable measurements and recording of data.

The measurement configuration is outlined in Section 2.1; more detailed descriptions of individual measurements are given in Section 2.2. Use of the minicomputer to control the system is described in Section 2.3 and measurement accuracy is discussed in Section 2.4.

2.1 Automated measuring system

The measuring equipment was housed in two mobile vans stationed at the ends of the repeater section under test. The remote van (Fig. 1) was positioned at the transmitting end and housed signal sources. The control van (Fig. 2) was stationed at the receiving end and contained the bulk of the measuring equipment, the minicomputer, and data-recording equipment.

Access to the pairs to be measured was provided in the apparatus case slots by probes (Fig. 3) permitting connection of side 1 and side 2 inputs and outputs to the control panels (Fig. 4) in the vans by 60-foot shielded patch cables. The specially designed control panels were the heart of the test arrangement. The manhole (service) repeater or a test repeater were inserted in the control panels at each end, which then allowed test equipment to be inserted into the T1 transmission path. Specially packaged, portable, automatic-protection switches were installed in the central offices at the ends of the measured span to allow removal of repeaters on one line at a time without manual patching by central office personnel.

Measurements of power sum and test repeater margin were performed with a special test repeater. The test repeater was a laboratory-modified automatic line build-out (ALBO) repeater with one side (regenerator) modified to provide the following features:

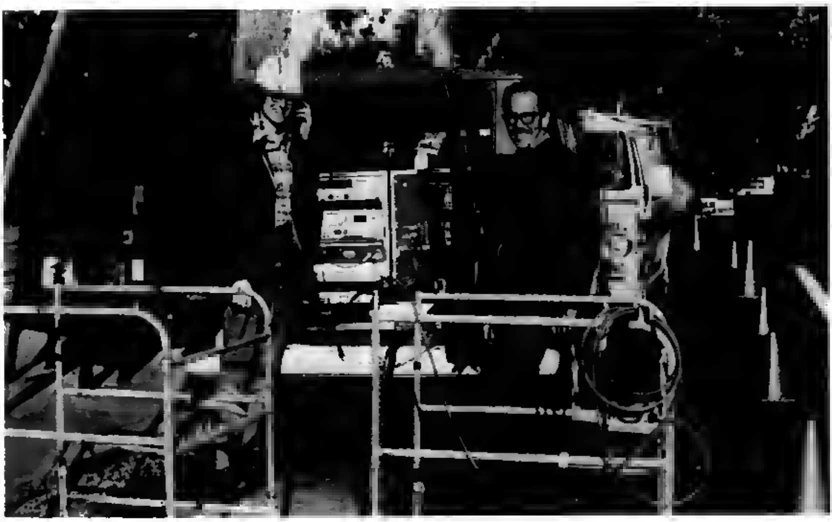

Fig. 1—Remote van containing signal sources.

(*i*) Access to the regenerator decision point for observation of the eye and for measurement of crosstalk power sum and signal level.

(*ii*) Option of regulated (normal) or fixed ALBO operation with monitoring of the ALBO current in both cases.

(*iii*) On/off control of the regenerator clocks.

Measurements were controlled by a minicomputer with 32K of memory (Section 2.3). It performed the following principal functions:

(*i*) Control of relays to set up the required measurement paths and instrument connections.

(*ii*) Setting of synthesizer frequencies.

Fig. 2—Control van containing measuring equipment.

Fig. 3—Apparatus case with access equipment.

(*iii*) Search routines for attenuator settings to produce voltmeter readings or error counts within a specified range.

(*iv*) Processing of voltmeter and counter outputs for recording on magnetic tape and for production of hard copy listing by a printing data terminal.

(*v*) Prompting of the operator for identification of repeater section, case, and slot.

A digital voltmeter and a counter interfaced with the computer via standard interfaces. All other interfaces with the computer were specifically designed for this experiment. A telemetry system, operating over any available pair capable of carrying an audio signal, was employed to transmit control signals from the control van to the remote van. A simplified block diagram of the measurement system is shown in Fig. 5.

2.2 Measurements

This section describes the individual measurements in detail; the relevant portion of the measurement equipment for each of the measurements is shown in Figs. 6 through 13. In these figures, the individ-

Fig. 4—Interior view of van showing control panels.

ual relays operated from the computer are identified by numbers in circles. The relay contacts are shown by the detached contact method, which indicates the nonenergized relay state by a single straight line through the transmission path for a closed contact and by a cross for an open contact. High isolation contacts are shown as double contacts.

2.2.1 Line resistance and simplex power current

The first measurement, cable resistance, was primarily intended to assure continuity of the transmission path between the control and remote vans once all signal and telemetry connections were made.

Line current was measured under normal operating conditions by measuring the voltage across a known resistor which was connected between the center taps of a 1:1 transformer, as shown in Fig. 6. A 5-½ digit DVM and a resistor of known value assured an accuracy of ±0.5 percent for the line-current measurement.

2.2.2 Longitudinal ac current

Low-frequency longitudinal current, band-limited by a filter (20 Hz to 1 kHz), was across a 10-ohm series resistor while a current probe was used to measure the high-frequency currents (1 kHz to 10 MHz), as shown in Fig. 7.

2.2.3 Peir loss at various frequencies

Pair-loss measurements at selected frequencies were performed with the following instruments, as shown in Fig. 8:

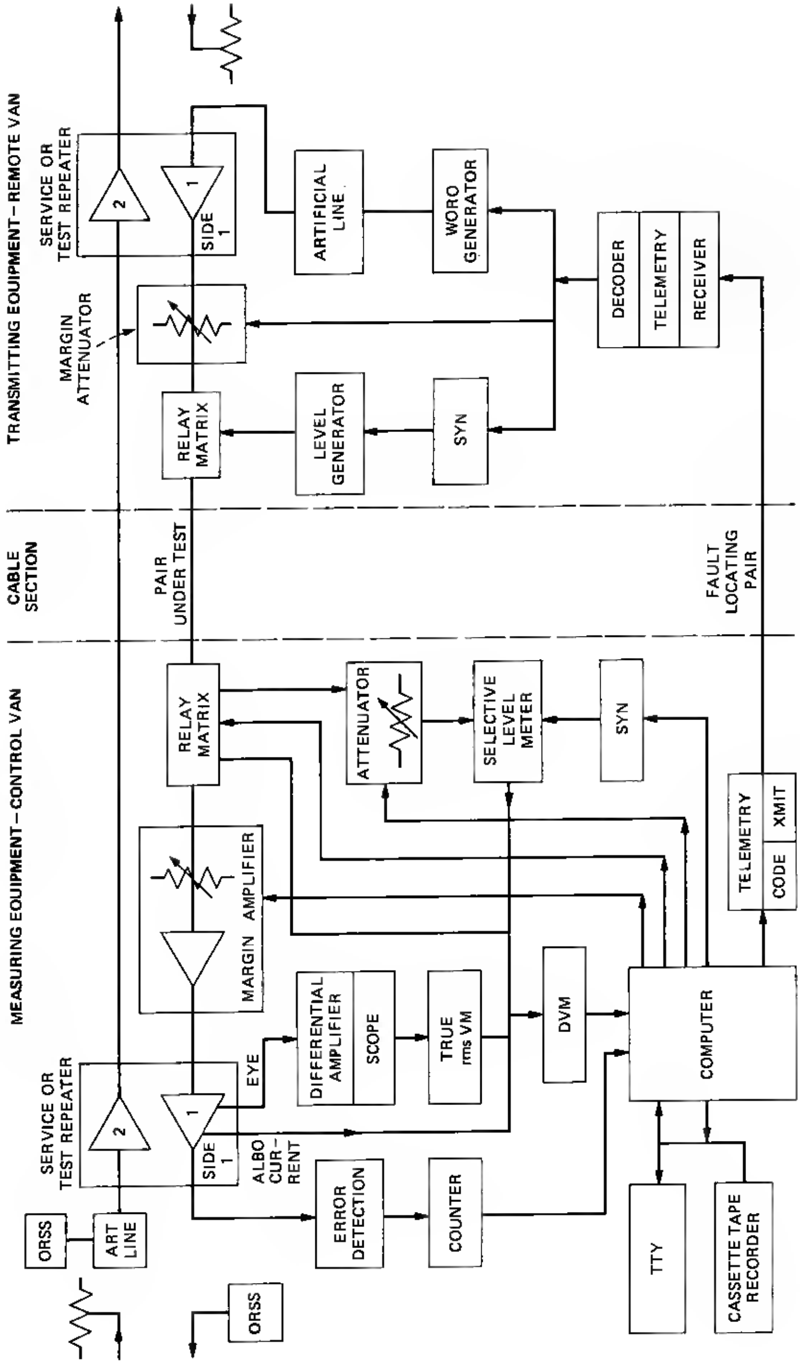

Fig. 5—Block diagram of measurement system.

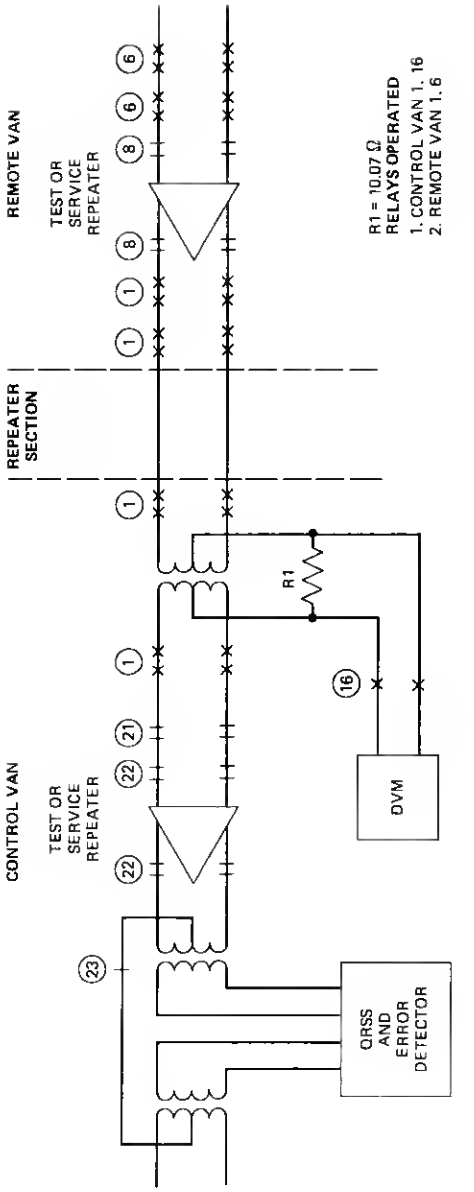

Fig. 6—Line current diagram.

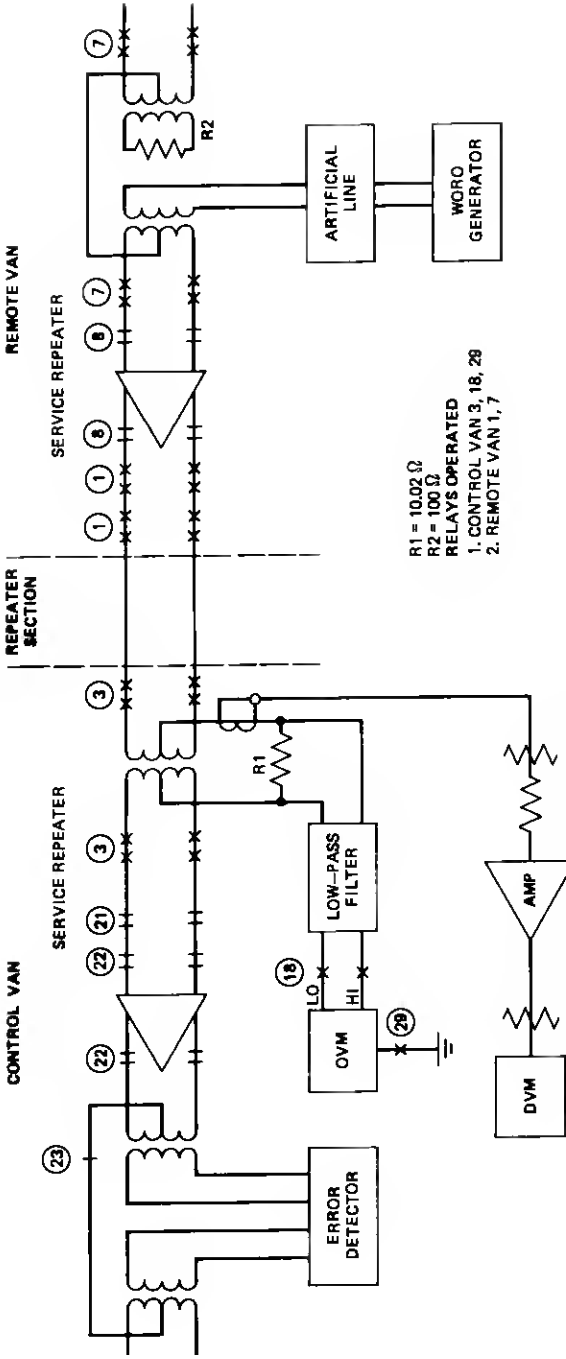

Fig. 7—System for low- and high-frequency longitudinal current measurement.

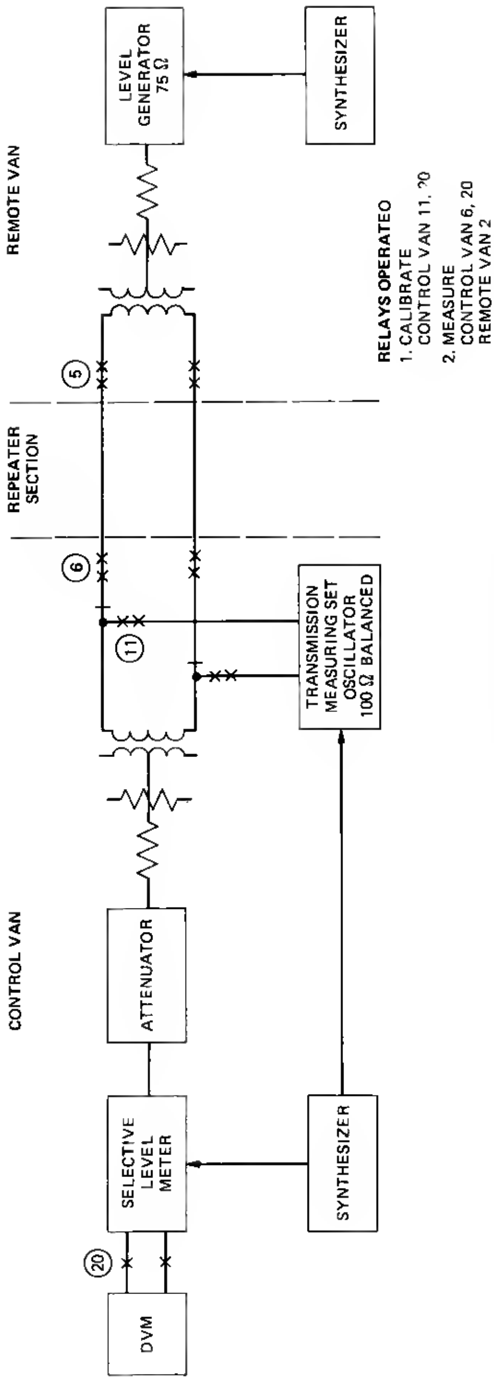

Fig. 8—Insertion-loss measurement system.

(*i*) A precision level generator was located at the remote end. Its frequency was controlled by a frequency synthesizer set by the computer from the control end via telemetry.

(*ii*) Located at the control end was a transmission measuring set (TMS) consisting of a stable level generator and a frequency selective level meter. The control frequency was also controlled by a synthesizer set by the computer. Auto-ranging detector operation was obtained by setting the detector to 80 dB of gain and applying signal to it via a programmable precision attenuator (0.1 dB resolution) controlled to produce a small range of dc output from the detector for measurements by the digital multimeter.

Measurement accuracy depended on the absolute level stability (better than 0.1 dB) of the level generators. The control-end detector (subject to drift) was automatically calibrated against the control-end generator (stable) before each measurement.

2.2.4 *Crosstalk coupling losses within apparatus case slot*

Figure 9 illustrates the measurement approach for within-slot crosstalk measurements. Measurements were performed with the control van's transmission-measuring set (TMS) described in Section 2.2.3. Six selective measurements (40-Hz detector bandwidth) at 772 kHz were made as follows:

(*i*) Side-1 input noise power with no signal on side-1 or side-2 outputs ("background" noise).

(*ii*) Side-1 input with side-1 output excited.

(*iii*) Side-1 input with side-2 output excited.

(*iv*) Side-2 input noise power with no signal on side-1 or 2 outputs (background noise).

(*v*) Side-2 input with side-1 output excited.

(*ii*) Side-2 input with side-2 output excited.

2.2.5 *Crosstalk power sum*

Measurements of crosstalk power sum at the repeater decision point were performed with the test repeater (Section 2.1). Since there was no T1 signal for the automatic line build-out (ALBO) to regulate properly, the preamplifier gain (and hence equalization) of the test repeater was fixed by forcing the ALBO current to the value it would have if regulating (operating normally) for a particular half-bit-rate pair loss. A convenient choice was 31.7 dB, which was within the loss range of the sections measured.

An oscilloscope with a differential plug-in amplifier monitored the noise signal at the regenerator decision point (repeater eye) relative to circuit ground and provided an unbalanced signal from its vertical output, which was measured by a true rms voltmeter. A dc voltage

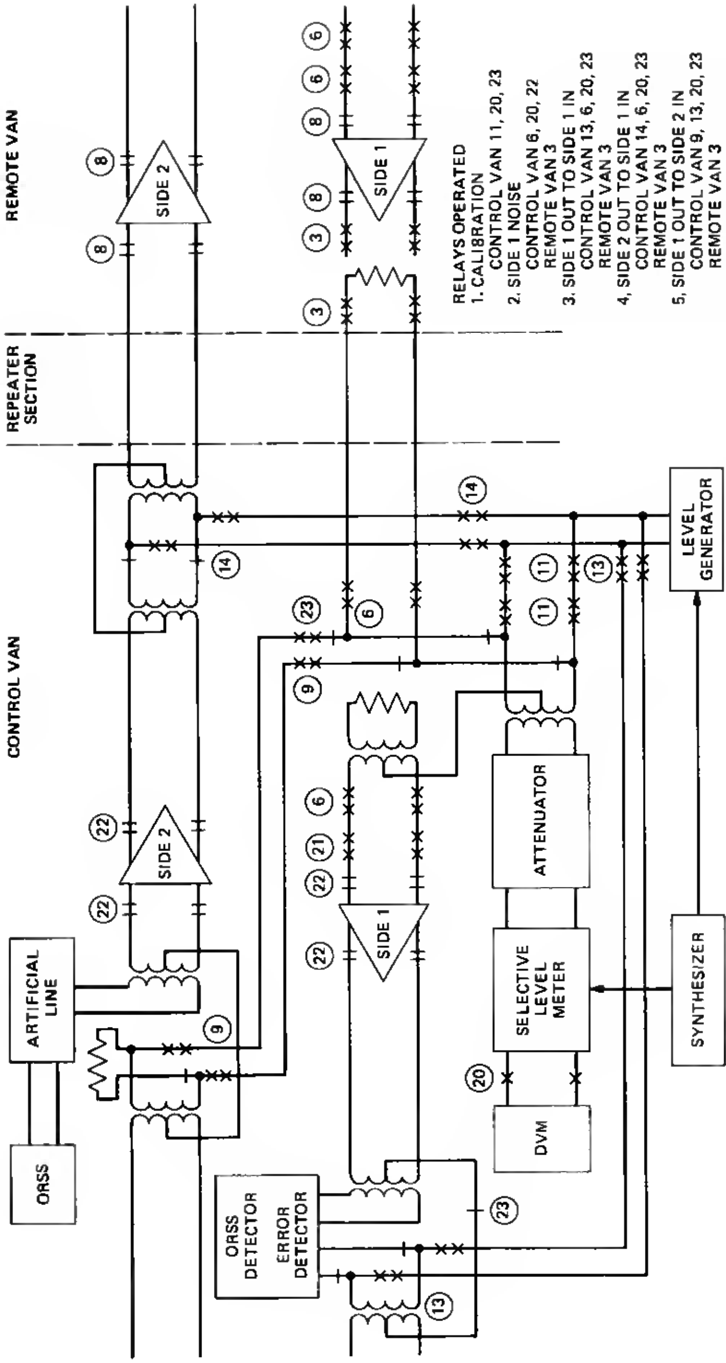

Fig. 9—Within-slot crosstalk measurement system.

proportional to the rms noise voltage was produced by the voltmeter and in turn measured by the digital dc voltmeter, which converted the dc voltage to a digital value suitable for the computer. An amplifier and variable attenuator under control of the computer and ahead of the test repeater brought tbe repeatered-line noise voltage within the measurement range of the true rms voltmeter.

2.2.6 Line margin

Line margin, the principal measure of performance, is defined as the number of dB that the signal-to-noise ratio of a repeater section must be reduced to produce a 10^{-6} error rate. For this measurement program, an amplifier-attenuator technique was used (Fig. 10). A quasi-random signal from a T1 word generator was injected through an artificial line (31.7 dB at 772 kHz) into the repeater input at the remote van. The repeater output was then attenuated by a remotely controlled 75-ohm attenuator, which was matched to the line with a repeating coil and matching pad. The minimum loss through this attenuator-transformer arrangement was 3.2 dB. In the control van, an amplifier-attenuator combination with a total available gain of 41.3 dB was switched in ahead of the repeater under test. The unbalanced-to-balanced conversion for this arrangement was accomplished with 1:1 transformers. A small inductor of 440 μF in series and 0.01-μF capacitor to ground were added to the simplex power loop to prevent amplifier oscillation. The net margin-measuring range for this arrangement was from 3.2 to 38.1 dB with 0.1 dB precision. The computer kept the attenuation at the remote van equal to the amplification at the control end to maintain the correct signal level at the repeater input. The system searched automatically for an attenuator setting that produced an initial error rate close to 10^{-3}. Four additional error-rate measurements were then made with the attenuator reduced in 1-dB steps, and the attenuation for a 10^{-6} error rate was calculated by polynomial interpolation. The functional relationship between attenuation and error rate is a measure of the peak factor of the noise.

The error rate (actually the bipolar-violation rate) was determined at the repeater output by a bipolar-violation detector and a counter. Two separate quasi-random signal sources (QRSS) energized the output pins of the apparatus case connector for the slot being tested to maintain normal within-slot crosstalk.

To obtain a measure of the variation of repeaters in the field, margin was measured for each line with the repeater found in the slot (service repeater) and with the test repeater (ALBO regulating normally).

2.2.7 Bit-rate and half-bit-rate output power of transmitting repeaters

Since the transmitted signal level of the service repeater in the remote van affects the measured service repeater margin, a measure-

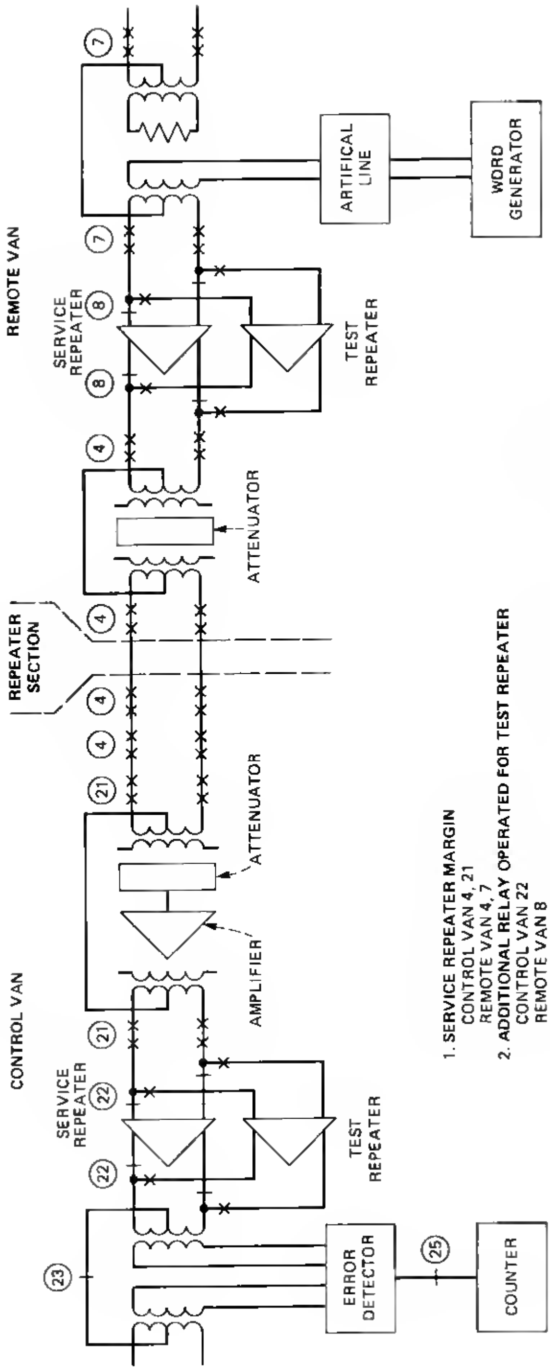

Fig. 10—System for service or test repeater margin measurement.

ment of the remote van's transmitting repeater output was made from the control van. This measurement was made with a 1500-Hz bandwidth at 772 kHz and 1.544 MHz when the remote service repeater was driven with an all ones signal produced by the remote van's word generator under telemetry control. The bit-rate power (1.544 MHz) is a measure of the balance between positive and negative pulses; the half-bit-rate power (772 kHz) is a measure of the output pulse amplitude of the transmitting repeater (after correction for line loss).

2.2.8 Crosstalk spectrum

The measurement of the crosstalk power spectrum was made at several frequencies with the level detector at the control van's repeater input while the remote end of the repeater section was terminated with a 100-ohm resistor (Fig. 11). The receiver was set for 100-dB gain and 1500-Hz bandwidth to achieve maximum sensitivity.

Measurements at three or more frequencies allowed calculation of the average ones density of the interfering signals and of the partitioning of the total crosstalk into cable far-end, cable near-end, and apparatus case near-end crosstalk (FEXT, NEXT, and ACXT).

2.2.9 ALBO current of test repeater

The test repeater's ALBO current was measured under two operating conditions; first, under the normal regulating condition to determine the ALBO setting as a function of cable loss for a normally regulating repeater, and second, under the fixed ALBO condition where the ALBO current was preset for a specific cable loss. This measurement consisted

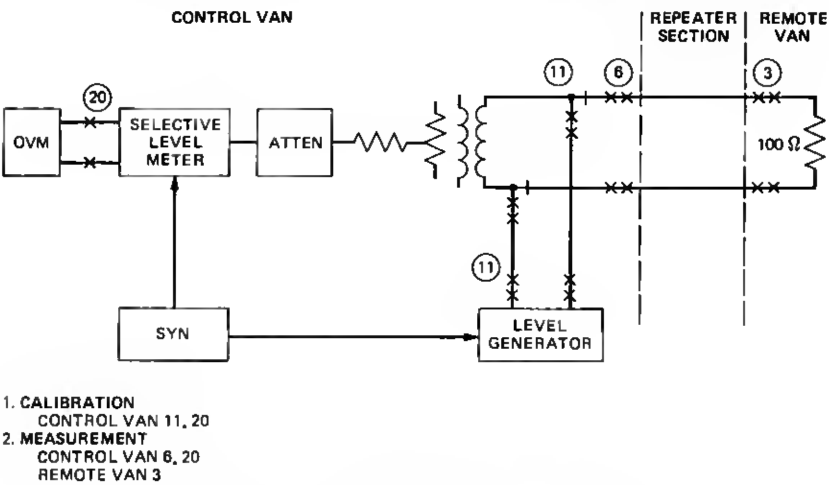

Fig. 11—System for measuring the crosstalk spectrum.

of a voltage measurement across a resistor in series with the repeater's ALBO diodes (Fig. 12).

2.2.10 Voltage amplitude distribution of crosstalk

On selected pairs, especially those with low margin, the probability distribution of the crosstalk voltage amplitude at the decision point of the test repeater was measured to determine possible departure from the Gaussian distribution that is generally assumed for margin analysis (Fig. 13).

The rms noise voltage measured at the repeater decision point (eye) was adjusted by computer control of a variable attenuator to a level V_0. A comparator, whose thresholds were also set by the computer, produced an output when the noise signal exceeded a selected value. The comparator output was clocked into a counter to determine the percentage of time for which the noise exceeded each level.

The threshold level was incremented from zero in integral multiples of the rms voltage until no counts were obtained in a 1-second interval (typically at 4 V_0). Then the level was decremented in four steps of one quarter of the rms voltage (e.g., 3.75 V_0, 3.50 V_0, 3.25 V_0, and 3.0 V_0), and 4-second counts were made to give high resolution and accuracy in the important "tails" of the distribution.

2.2.11 Service repeater margin and eye opening

Both the *repeater*-margin (not to be confused with the *line* margin) and eye-opening tests were designed as independent measurements of service-repeater performance. For these tests, the repeaters are operated on a 31.7-dB artificial line. The eye-opening test employed a quasi-random signal in which the amplitude of a pulse in every 16th time slot could be varied from zero to full amplitude. This measurement was intended to directly measure the service-repeater eye degradation due to the intersymbol interference resulting from imperfect equalization. The eye of the service repeater was closed by reducing the amplitude of a pulse representing a "one" or increasing the amplitude of a small pulse substituted for a "zero" and measuring the error rate.

The service-repeater margin was measured by determining the amount of suitably filtered broadband Gaussian noise necessary at the repeater input in order to cause a given error rate with a quasi-random signal. In addition to the effect of the repeater-eye degradation mentioned above, this test also reflected variation in the noise filtering of the T1 repeater preamplifier.

The intent of these tests was to characterize the performance of the service repeater independently of the T1 plant in which it normally operates.

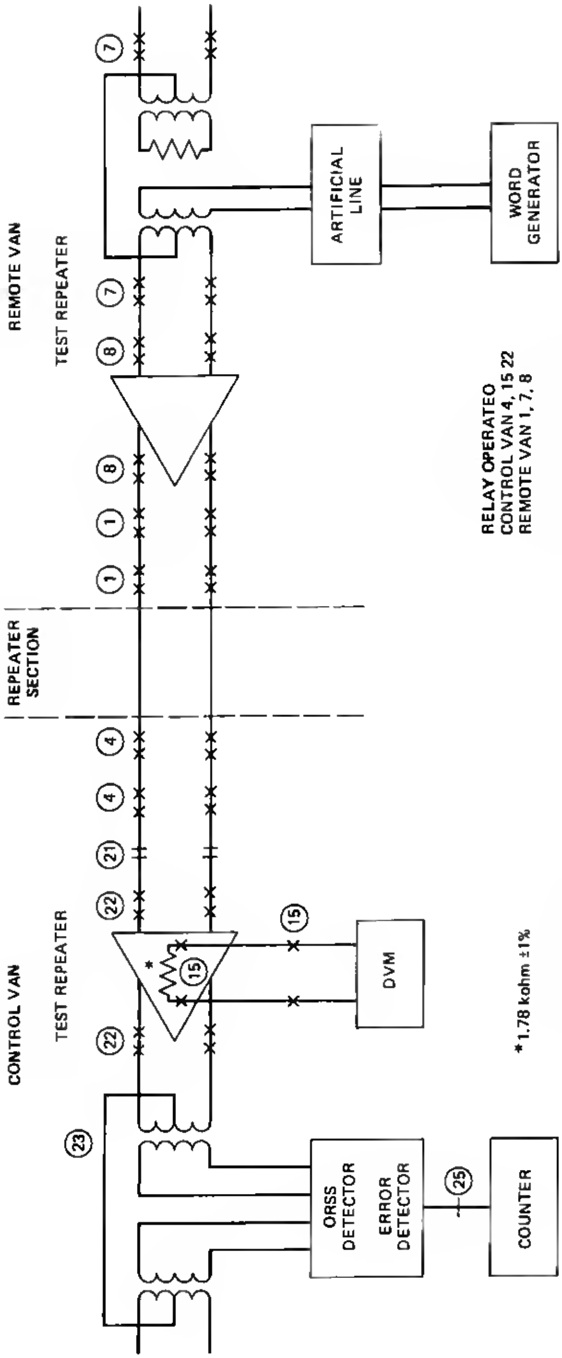

Fig. 12—System for measuring the ALBO current of the test repeater.

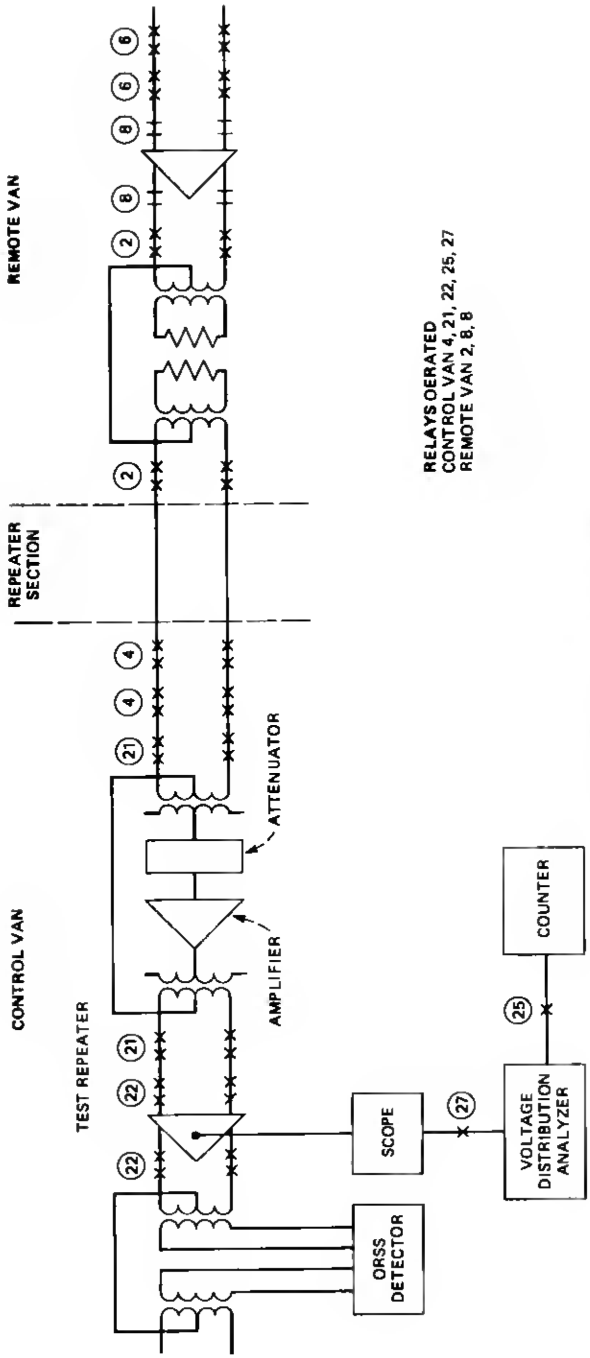

Fig. 13—System for measuring the noise-voltage distribution.

2.2.12 *Test-repeater calibration checks*

Several checks of the test-repeater performance were provided in this experimental arrangement. For example, the test-repeater-equalizer gain shape and stability were measured under fixed ALBO conditions by injecting a single frequency from the level oscillator and measuring the resulting output at the repeater eye witb the rms voltmeter. To test for any drift in the test-repeater ALBO current, a quasi-random signal was directed through an artificial line to the regenerator input while the ALBO current was measured.

2.3 *Computer measurement programs*

A new operating system for the minicomputer was developed for field measurements to satisfy the following special requirements:

(*i*) Provide a core-based system for quick start-up and execution of measurement programs as well as decreased dependence on magnetic recording media (tape or disk) during long periods of operation in hostile environments.

(*ii*) Provide a programming language with a set of basic commands for the sequential control of relays and measurement instruments and with the capability for algebraic calculations and conditional branching.

(*iii*) Provide for the creation and saving of named measurement sequences (programs) that may thenceforth be called by name in the same manner as the basic commands.

(*iv*) Eliminate cumbersome compilation and loading procedures when creating, modifying, or executing measurement programs so that the maximum time may be spent on making actual measurements.

The latest version of this system occupied the entire 32,768 words (16 bits) of the minicomputer, where the operating system used about 20,000 words and the measurement programs filled up the rest of the core. Since core storage is nonvolatile, start-up of the system required only power on and a manual jump to a starting address. Only in those cases where previous versions of the operating system or measurement programs were desired (or for certain operator errors or hardware failures) was it necessary to load tbe computer memory from an external medium (tape or disc).

The structure of the command language designed is very simple. Every command consists of a command name followed by a list of parameters, where all items are separated by spaces. Commands may be preceded by statement numbers, which may be used in control commands (e.g., GOTO) to refer to the given command. Multiple commands may be entered on one line, separated by semicolons. A line entered at the terminal may or may not start with a line number. Command lines entered without a beginning line number are executed

as soon as entered. Command lines entered with a line number are stored in a program area as part of a current program being built up or modified. The current program may be saved under a new name, or may replace a previously saved program, and then becomes available for execution as a new command.

The types of basic commands available in the operating system were as follows:

(*i*) Instrument commands—e.g., "SYNN 772" sets the control van frequency synthesizer to 772 kHz and "DVM X" causes the digital voltmeter to make a reading and store the results in the variable X.

(*ii*) Program control commands—e.g., "RANGE X A B 1 2 3" causes program execution to jump to statement 1 if X is less than A, to statement 3 if X is greater than B, and to statement 2 if X is in the range A to B inclusive.

(*iii*) Algebraic calculations—e.g., "LET $A = B + C / D$" calculates the quantity $(B + C)/D$ and stores the result in A.

(*iv*) Trigonometric functions—e.g., "COS A X" calculates the cosine of A and stores the result in X.

(*v*) Input-output statements—e.g., "*WR* 2 (*F*6.2, *F*8.1) A B" writes the numbers A and B to the terminal in the format indicated.

(*vi*) System commands—e.g., "SAVE MEASCUR" saves the program residing in the current working area into its own memory area under the name MEASCUR.

Since new programs may be named, saved, and thenceforth called in a manner identical to the basic commands, a hierarchy of programs may be built up, where programs at a given level use previously constructed programs as building blocks. When a standard set of field measurements was being made, the last program was usually just a list of the measurements to be made, in the desired order. For example, a program named MEAS1 (which may be called by simply typing "MEAS1" on the terminal) may look like the following:

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100 RES; CUR; IL; PSUM; MARGIN
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and would perform the measurements of line resistance, simplex powering current, pair insertion loss, crosstalk power sum, and line margin in the indicated order.

2.4 Measurement accuracy

Tests were performed to evaluate the equipment accuracy. Measurements of total within-slot crosstalk coupling losses exhibited a Gaussian distribution to about 100 dB (2.8 sigma point) indicating no truncating within this region due to detector sensitivity limitation. Crosstalk coupling losses within the measurement equipment itself were greater than 114 dB for all crosstalk measurement paths. In

addition, short-term measurement stability tests under field conditions revealed only small variations for other measurements. Ten repeated measurements made on three different repeater sections resulted in average standard deviations of 0.03, 0.19, 0.18, and 0.04 dB for power sum, test-repeater margin, service-repeater margin, and 772-kHz insertion loss, respectively.

An upper bound on long-term measurement accuracy for insertion loss can be inferred from field results. A sigma of 0.16 dB has been determined for the measurements of low-frequency insertion loss for each of seven complete cable cross-sections. This total variation includes actual pair-loss variations so that the TMS variation alone was less than 0.16 dB.

Crosstalk power sum was measured twice within less than one minute under similar conditions on each of 503 T1 pairs in one measurement program. The distribution of the difference had a standard deviation of less than 0.1 dB.

III. END-SECTION MEASUREMENTS

The measurements performed on end sections (those repeater sections adjacent to a central office) were carried out in a single-ended mode as opposed to the double-ended master-slave van configuration employed in the T1 intermediate-section measurements. That is, equipment was employed only at the receiving end of the repeater section (the central office) rather than at both ends.

3.1 Test configuration

The measurement procedure called for removal of the office service repeater from its slot, attaching an adapter to its edge connector, and reinserting it into the slot. The adapter allowed the incoming signal pair to be connected to the external measuring equipment while the line-powering current was maintained by the original office repeater reinserted into its slot. The incoming signal was passed through a variable (flat) gain broadband amplifier made up of an attenuator and a video amplifier connected in tandem. This combination provided a range of a available gain of −19.1 dB to +41.9 dB, adjusted nominally to 0.0 dB.

Figure 14 represents the test equipment configuration, which employed an office repeater as the test repeater. Modifications were made to permit external monitoring of the test repeater's ALBO current (I_{ALBO}), decision threshold voltage (V_{th}), and the (broadband) rms noise voltage (V_{rms}) present at the eye of the regenerator. In addition, ALBO current and threshold voltage were allowed to operate at their normal levels or fixed to externally provided reference levels.

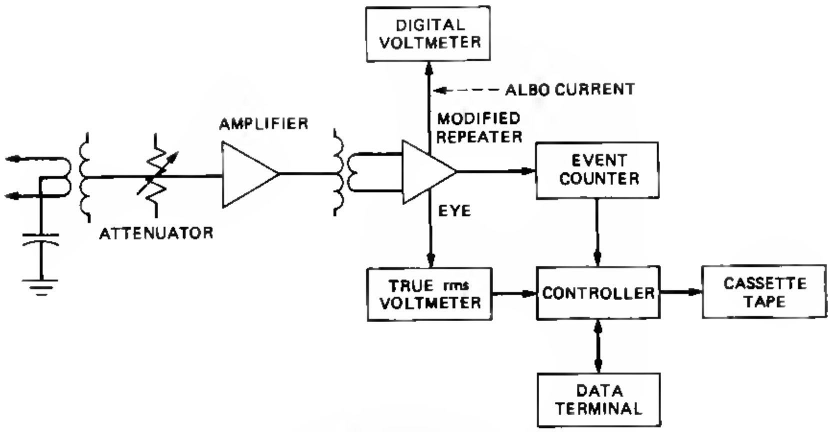

Fig. 14—End-section test configuration.

The regenerator output pulse stream was routed (with bipolar to unipolar conversion) to a digital counter, and the regenerator V_{rms} to an rms voltmeter. Outputs of both these instruments were interfaced to a microprocessor-driven measurement controller that performed operator prompting and interaction, measurement-algorithm control, and data-logging functions.

3.2 End-section measurements

Line margin at the 10^{-6} error rate was determined for end sections by amplifying crosstalk noise without signal on the line and counting output pulses. This was done by disabling the internal clock-extraction circuitry of the test repeater and inserting a local 1.544-MHz clock signal, thus enabling continuous sampling of the noise at the repeater's decision point, independent of input-signal timing energy. The test repeater was set up by adjusting and maintaining its threshold at one-half of the peak signal, ($V_{P/2}$), and its ALBO current at a level corresponding to the section length being measured. Then, with the test repeater operating essentially as a strobed comparator, flat gain was added at its front end until noise peaks present on each incoming line exceeded the threshold voltage ($V_{P/2}$), and began producing "ones" at the repeater's output. The margin was then taken as the amount of added gain required to produce pulses at a 10^{-6} rate. Note that this margin was in effect measured with a perfect eye; that is, the noise occupied fully 50 percent of the peak signal before producing an error. Thus, margins under operating conditions will be on the order of 4 dB lower to account for intersymbol interference under normal operating conditions.

In addition to margin, two parameters were measured to characterize the amplitude distribution of noise on end section lines. While the test repeater was producing pulses at a 10^{-6} rate, the rms value of the noise present at the repeater eye was measured and recorded. This value was used to determine the "noise peak factor," defined as the ratio "peak" to rms noise voltage in dB. In this instance, the peak voltage was taken to be the regenerator threshold voltage (V_{th}) exceeded 0.0001 percent of the time, corresponding to a 10^{-6} error rate, and was maintained in the test repeater at $V_{P/2}$.

The second noise-distribution indicator was provided by degrading the signal-to-noise ratio in steps of 1.0 dB and recording the repeater's error rate at each step. The set of points obtained may then be compared to the theoretical probability of error for Gaussian noise.

IV. CONCLUSION

The measurement equipment for the T1 characterization program has proven reliable, accurate, and versatile under actual field conditions. In fact, over 100,000 data items or a total of about 3,000 repeater section lines were measured in 1977 and 1978 with no more than 10 hours of down time due to computer and transmission measuring set failures. High accuracy was maintained throughout the experiment by the elimination of human recording errors and the high inherent accuracy of the automated test procedures. Program modifications were readily accomplished throughout the experiment, permitting modification of existing programs for increased operational efficiency and the inclusion of new test programs.

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